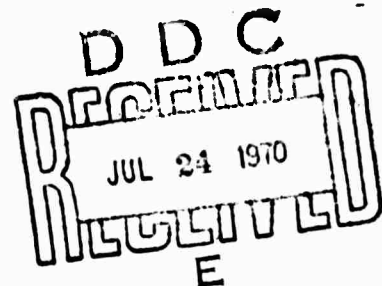AD709044

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STRESS-CORROSION PROPERTIES
OF
HIGH-STRENGTH PRECIPITATION-HARDENING STAINLESS STEELS
IN
3.5% AQUEOUS SODIUM CHLORIDE SOLUTION

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STRESS-CORROSION PROPERTIES OF HIGH-STRENGTH,
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C. S. Carter, D. G. Farwick,

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ABSTRACT

The plane-strain fracture toughness K_{Ic} and stress-corrosion
threshold K_{Iscc} have been determined for the following high-strength,
precipitation-hardening steels: 17-7 PH (RH 950, TH 1050), PH 15-7Mo
(RH 950, TH 1050), AM 355 (SCT 850, SCT 1000), AM 362 (H 900, H 1000),
AM 364 (H 850, H 950), 17-4 PH (H 900, H 1000), 15-5 PH air melted and
vacuum melted (H 900, H 1000), PH 13-8Mo (H 950), and Custom 455 (H 950).
Correlations of K_{Iscc} with service performance, smooth-specimen test
data, and chemical composition are discussed.

INTRODUCTION

In the numerous investigations conducted to determine the stress-
corrosion cracking properties of high-strength, precipitation-hardening
stainless steels, smooth, unnotched specimens have customarily been
tested. The problems associated with interpreting smooth-specimen data
and translating it into design considerations have been emphasized by
Brown (1,2). However, the development of precracked-specimen testing
and data analysis in terms of linear elastic fracture mechanics has
provided a more rational basis for alloy selection and information that
can be directly used in design considerations. Unfortunately, only a
limited amount of data from precracked specimens has been reported for
precipitation-hardening stainless steels. The present investigation
therefore had the following objectives:

1. Establish for high-strength, precipitation-hardening stainless
   steels in various heat-treatment conditions the plane-strain

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stress-intensity thresholds K_{Iscc} below which stress-corrosion cracking does not occur.

2. Correlate the K_{Iscc} with known service performance.
3. Determine whether stress-corrosion cracking properties obtained from precracked specimens correlate with published data obtained from smooth specimens.
4. Examine the effect of composition on the K_{Iscc} of these steels.

The environment selected was 3.5% aqueous sodium chloride solution, which has been used in many previous stress-corrosion tests on both smooth and precracked specimens, and possibly simulates an aggressive service environment.

The development and properties of most of the commercially available stainless steels were reviewed recently (3,4); therefore, only factors essential to this study are discussed here. These steels generally contain 10% to 20% chromium, up to 12% nickel, and one or more elements, such as Ti, Al, Nb, Cu, or Mo, given in approximately decreasing order of strengthening effectiveness (5), to promote precipitation hardening of the martensite matrix.

High-strength, precipitation-hardening stainless steels may be divided into two major categories—semiaustenitic and martensitic. Semi-austenitic steels have a carbon content of 0.06 to 0.15 to promote austenite stability. They are austenitic in the annealed condition and, as such, have good formability. Transformation to martensite is accomplished either by a trigger anneal (TH condition) to precipitate carbides and raise the martensite start (M_s) temperature or by subzero cooling below M_s (RH condition). The desired strength is subsequently attained by aging at 900° to 1150°F. Unfortunately, the chemical balance needed leads to δ-ferrite formation and grain-boundary carbide precipi-tation (6), which results in low transverse ductility.

The carbon content of martensitic steels is maintained at low levels. The alloy content is balanced to provide an essentially martensitic struc-ture at room temperature. However, increasing the alloy content, with the exception of Co and Al, lowers M_s, thus promoting retention of aus-

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tenite. Also, most age hardening elements promote δ-ferrite formation (5). High strength is attained by aging at temperatures similar to those used for the semiaustenitic steels.

Because of the transverse ductility problems associated with the semiaustenitic stainless steels, most development in recent years has been directed to the martensitic types. Steels for high-temperature applications that contain 15% to 20% Co to maintain elevated-temperature strength have also been developed. The properties of these alloys have been discussed elsewhere (7,8).

MATERIALS AND HEAT TREATMENT

The chemical compositions of the steels studied in the present investigation are given in Table 1 together with the form in which the steels were procured. Where possible, the heat treatments selected (Table 2) were those known to be used for aerospace applications. Stress-corrosion resistance of most of the semiaustenitic steels (except AM 355) was determined in both RH and TH conditions. The martensitic steels were, in most cases, evaluated after aging to peak strength and after overaging.

EXPERIMENTAL PROCEDURE

Round tension specimens (0.25 in. in diameter) and single-edge-notched specimens (Fig. 1) were machined from the materials with their major axes parallel to the longitudinal grain direction. The specimens were heat treated as blanks and subsequently ground to final dimensions. Notched specimens were fatigue cycled after heat treatment to produce a precrack approximately 0.1 in. long at the notch root.

Tensile mechanical properties were determined in duplicate at room temperature using a strain rate of 0.005 in./in./min to yield and 0.2 in./in./min to failure. The plane-strain fracture toughness K_{Ic} was determined in duplicate at room temperature by loading single-edge-notched specimens (Fig. 1a) in three-point bending. The tests were performed and the results analyzed according to the recommended ASTM procedure (9).

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To evaluate stress-corrosion resistance, fatigue precracked single-edge-notched specimens (Fig. 1b) were hydraulically sustain loaded to selected initial stress-intensity K_{Ii} levels in cantilever bending using the procedure described by Brown (1). The stress intensity was calculated according to the relationship given by Brown and Srawley (10) for pure bending. The 3.5% aqueous sodium chloride solution was dripped continuously into the notch, starting just prior to load application. Specimens were exposed until the specimen broke or until a minimum period of 500 hr had elapsed. If fracture did not occur, the specimens were examined macroscopically for evidence of crack growth. Regions of stress-corrosion crack growth were examined by fractographic techniques to determine the mode of fracture.

RESULTS AND DISCUSSION

The microstructure of the heat-treated semiaustenitic steels consisted of martensite and 10% to 20% δ ferrite. A heavy concentration of carbide precipitates was apparent at the δ-ferrite boundaries in all semiaustenitic steels except AM 355 with the modified SCT 1000 heat treatment where carbides were uniformly distributed through the martensite matrix. Ferrite was absent from all the martensitic steels except 17-4 PH where approximately 2% was present.

The tensile and fracture toughness properties of the steels studied are tabulated in Tables 3 and 4, respectively. The thickness (0.48 in.) of the single-edge-notched specimen used in this study was insufficiently large for valid K_{Ic} values to be determined for the tougher materials. These are identified in Table 4.

During stress-corrosion testing, specimens of several steels failed while being loaded to K_{Ii} levels within 80% of K_{Ic}. There was no evidence of subcritical growth in these specimens, so it was concluded that the mechanical fractures were a result of a wide distribution in K_{Ic}. Because of this, the maximum K_{Ii} used was usually limited to approximately 85% of the mean K_{Ic} shown in Table 4. The stress-corrosion test results for all materials are shown as curves of K_{Ii} versus time to fai-

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ure in Figs. 2 to 11 and the K_{Iscc} values are summarized in Table 4. Dashed lines indicate that no stress-corrosion crack growth was observed at the highest K_{Ii} level used.

The K_{Ic} values obtained in this study for 17-4 PH (H 900), PH 15-7Mo (RH 950), and AM 355 (SCT 1000) were in close agreement with previously reported data; however, the values for 17-7 PH (RH 950 and TH 1050) and PH 15-7Mo (TH 1050) were approximately 50% lower (11). The K_{Iscc} values reported by Freedman (12) for 17-4 PH (H 900) and AM 355 (SCT 850) are comparable with those obtained in this study. However, Freedman reported a K_{Iscc} of 36.7 ksi $\sqrt{in.}$ for AM 355 (SCT 1000), whereas the present study found no susceptibility in AM 355 for this heat-treatment condition. Reasons for these discrepancies are not apparent.

As shown in Figs. 12 and 13, both K_{Ic} and K_{Iscc} decreased inversely with strength level. There was a general trend for K_{Iscc} to increase with K_{Ic} (Fig. 14), but high toughness was not necessarily associated with immunity to stress-corrosion cracking. For example, the highest K_{Ic} value recorded was 131 ksi $\sqrt{in.}$ for AM 364 (H 850), but the K_{Iscc} for this material was 97 ksi $\sqrt{in.}$ On the other hand, some steels with lower fracture toughness were immune to stress-corrosion cracking.

In general, the fracture toughness and stress-corrosion resistance of the martensitic steels were significantly higher than those of the semiaustenitic steels. Presumably, the absence of δ ferrite and of embrittling grain-boundary carbides from most martensitic steels was responsible.

Several observations may be made on the stress-corrosion properties of the semiaustenitic steels. The properties achieved in AM 355 by the modified SCT 1000 heat treatment indicate the improvement that can be obtained with a uniform carbide distribution. Transformation to martensite by a thermal treatment (TH 1050) gave only a slightly higher K_{Iscc} than the refrigeration treatment (RH 950) in PH 15-7Mo. The 17-7 PH steel appeared to have similar resistance in both heat-treatment conditions, although an insufficient number of specimens prevented a clear distinction. The rate of stress-corrosion crack growth was determined

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on the 17-7 PH (TH 1050) steel by visual observation. The growth rate was constant at 0.003 in./min over the stress-intensity range studied—20 ksi $\sqrt{in}$. to K_{Ic}.

Overaging, as compared with aging to peak strength, increased both fracture toughness and stress-corrosion resistance of semiaustenitic (AM 355) and martensitic steels. As indicated in Table 5, the stress-corrosion properties showed the greater improvement.

The superior K_{Ic} and K_{Iscc} values of the air-melted over the vacuum-melted 15-5 PH steel were unexpected in view of the claimed benefits of vacuum processes. The materials had similar microstructures with no evidence of δ ferrite or significant differences in grain size. The larger section size of the vacuum-melted material (Table 1) may have been a contributory factor.

Fractographic examination revealed that the stress-corrosion cracks in both the semiaustenitic and martensitic steels invariably propagated in an intergranular manner. Typical fractographs are shown in Figs. 15 and 16.

DESIGN APPLICATION

The applied stress-crack length relationship for initiation of stress-corrosion crack growth can be determined by linear elastic fracture mechanics (13). Surface cracks are a common source of fracture initiation and in the case of stress corrosion provide for the ingress of the corrosive environment. Under these circumstances the applied stress σ and critical crack depth a are related by the expression (14)

$$K_{Iscc} = 1.21 \pi \sigma^2 (\frac{a}{Q})$$

where Q depends on the crack shape and ratio of σ to σ_{ys}. For surface cracks with a length:depth ratio exceeding 10, the value of Q is within the range 0.8 to 1.0; the actual value depends on σ/σ_{ys}. Relationships are shown in Fig. 17 for the steels found to be susceptible to stress-corrosion cracking. These indicate that in the most susceptible materials (17-7 PH, PH 15-7Mo, AM 362) cracks less than 0.010 in. deep could

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result in stress-corrosion crack growth when the applied stress exceeds about half the yield stress. For stress levels approaching yield point magnitude, cracks 0.002 or 0.003 in. deep would be sufficiently large. Cracks of this order of size would not be detected by conventional nondestructive testing procedures. Even if the limit of inspection is 0.050 in., there will be a definite risk of stress-corrosion cracking at stress levels approaching the yield point in all the materials found to be susceptible.

It has been tentatively deduced (15) from the results of tests on smooth specimens that the applied stress on semiaustenitic steels can be safely limited to 80 to 90 ksi. As discussed above, a surface crack approximately 0.010 in. deep in 17-7 PH or PH 15-7Mo steels could initiate stress-corrosion cracking in hostile environments at this stress level, and the suggested "safe stress" appears to be too optimistic. In the case of the martensitic steels aged to 165-ksi yield strength, the "safe stress" was suggested as 150 ksi. The 17-4 PH and 15-5 PH alloys heat treated (H 1000) to 165 ksi strength level in the present study exhibited immunity to stress corrosion. However, there is the additional possibility of brittle fracture initiation. The K_{Ic} of both materials at the strength level was 120 ksi $\sqrt{in.}$, and the critical flaw depth for rapid brittle fracture would be approximately 0.15 in. at 150-ksi applied stress. Whether flaws of this size would be detected would depend upon the inspection techniques employed and the component geometry.

SERVICE PERFORMANCE

A 1967 publication (15), reviewing the service performance of high-strength stainless steels, concluded that no components fabricated from semiaustenitic steels had failed by stress corrosion and that failures in martensitic PH steels were almost nonexistent. More recently, however, failures have been reported for 17-7 PH springs (RH 950 and TH 1050 conditions) used in the Saturn V rocket stages (16). The results of tests in the present study have demonstrated the low stress-corrosion resistance of 17-7 PH in these heat-treatment conditions. As shown in Fig. 17, small flaws or shallow surface pits could lead to failure. Stress-

corrosion-initiated service failures have also been reported for 17-4 PH
in the H 900 condition (17) in certain applications. The results ob-
tained from the tests on precracked specimens would not have predicted
such behavior. High δ-ferrite content, directionality effects, or a
specific environment may be responsible. Also, service failures from
hydrogen embrittlement have occurred in 17-4 PH (H 900) bolts fastened
to aluminum in a wet environment (18). Otherwise, service experience
with the martensitic alloys 17-4 PH (H 1000), 15-5 PH, and PH 13-8Mo
appears to have been very good and is in agreement with the results
obtained in this study. Service performance data are not available for
the other materials evaluated.

COMPARISON OF DATA FROM TESTS ON PRECRACKED AND SMOOTH SPECIMENS

A number of test specimen geometries and loading systems have been
used to evaluate stress-corrosion resistance on smooth, unnotched speci-
mens. It is generally believed that with these specimens pitting is a
necessary precursor to stress-corrosion crack initiation. Furthermore,
the extent of stress-corrosion crack growth is controlled by fracture
toughness (plane stress or plane strain) of the material, which further
depends upon thickness considerations. All these factors contribute to
the fracture resistance, as measured by time to failure, although their
individual contributions cannot be isolated. With precracked specimens,
on the other hand, the necessity for pitting is eliminated, and the re-
sistance to stress-corrosion cracking is measured directly as K_{Iscc}. In
view of the large amount of information from smooth specimens that is
available, a comparison of the data generated by both types of specimen
was considered desirable.

Results obtained from smooth specimens indicate that PH 15-7Mo is
more resistant to stress corrosion than 17-7 PH and that resistance in
the TH condition is superior to that in the RH condition (15,19). How-
ever, the results obtained in this study show similar K_{Iscc} values for
the two materials and that the threshold for material in the TH con-
dition is only slightly higher than that for material in the RH con-
dition. The first discrepancy may result from the higher molybdenum
content of the 15-7Mo steel, which would improve the pitting resistance

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of stainless steel and would prolong the failure time for smooth specimens. The second discrepancy can be explained as follows. Assume that stress-corrosion crack initiation occurs in smooth specimens when the acuity and depth of a corrosion pit are sufficient to exceed K_{Iscc} for the applied stress imposed. Then the critical depth of pitting in material in the two heat-treatment conditions will be proportional to the square of the ratio of the K_{Iscc} values, i.e., $(19/14)^2 = 1.84$ for PH 15-7Mo. It follows that in material in the TH condition a pit almost twice as deep would have to develop to initiate stress-corrosion cracking. If the contribution of pitting to failure time in smooth specimens is large, as seems likely in these materials, then the greater pit depth required would lead to a significant increase in failure time and to the inference of much enhanced stress-corrosion resistance.

It has been reported that smooth specimens of 1-in.-dia bar of AM 362 (H 900) withstood an applied stress of 90% of the yield strength for 140 days without failure in 5% salt spray (3), thereby implying good stress-corrosion resistance. This may be contrasted with the K_{Iscc} obtained from precracked specimens—12.5 ksi $\sqrt{in.}$, which indicates low stress-corrosion resistance. Possibly AM 362 has good pitting resistance and in the absence of a stress raiser exhibits apparent immunity to stress-corrosion cracking.

Data from smooth specimens of PH 13-8Mo (H 950), 17-4 PH (H 1025), 15-5 PH (H 1025), and Custom 455 have indicated good stress-corrosion resistance (3) and are therefore in agreement with data from precracked specimens, reported in Table 4.

EFFECT OF COMPOSITION

The presence of ferrite and grain-boundary carbides makes the interpretation of composition effects in the semiaustenitic steels difficult, therefore only the martensitic steels were examined. However, composition effects are not easily interpreted in these steels either, since the compositions vary widely, and the effects of individual elements cannot be isolated. In addition, comparisons should be made only at specific strength levels. These may be achieved by either peak aging

or overaging, depending upon the alloy content, thus introducing a heat-treatment variable. Nevertheless, correlations of K_{Ic} and K_{Iscc} with composit n were sought in the 190- to 200-ksi tensile ultimate strength range in which the majority of data was obtained.

As shown in Fig. 18, K_{Ic} and K_{Iscc} appear to be adversely affected by low nickel and high chromium contents. The effect of age-hardening elements is shown in Fig. 19. Aluminum appears to be more beneficial than titanium and copper. Titanium, as represented by the AM 362 steel, was the most harmful. On the other hand, Custom 455, containing approximately 1.3% titanium, exhibits high properties when overaged (20). Nevertheless, the trends indicated are in agreement with previously published data on the effect of alloying elements on tensile reduction of area (5).

The trends apparent in Figs. 18 and 19 suggest that development of future martensitic alloys should maintain chromium at the lowest level compatible with the corrosion resistance required and nickel at the highest possible level. Aluminum appears to be an attractive age-hardening element. In addition, published data (5) suggest that molybdenum would be a suitable choice. The use of titanium in significant amounts appears to be questionable. Also, consideration should be given to designing alloys in which the desired strength level is achieved by overaging. It is interesting to note that a recently developed alloy (21), designated IN736, has a composition which corresponds closely to that suggested above: 10Ni-10Cr-2Mo-0.3Al-0.2Ti-0.02C. Nominally a 180-ksi alloy, IN736 is reported to have exceptional toughness and good stress-corrosion resistance.

EFFECT OF THICKNESS

Recent studies (22) have suggested that plane-strain conditions exist when material thickness exceeds 2.5 $(K_{Iscc}/\sigma_{ys})^2$. Below this limit the stress-corrosion threshold may increase by relaxation of constraint. Applying this criterion to the stress-corrosion-susceptible alloys provides an estimate of the critical thickness below which an improvement in stress-corrosion resistance could be expected. As shown

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in Table 6, very thin sheets must be used in order to exploit the thickness effect in the most susceptible materials. Of course, this ignores the possible benefits of hot or cold working, but the suggested values are supported by previously published data. For example, tests on precracked specimens of 0.1-in.-thick PH 15-7Mo (RH 950) indicated a K_{Iscc} below 21 ksi $\sqrt{in.}$ (23). This agrees with the value of 14 ksi $\sqrt{in.}$ determined in the present study on a 0.5 in.-thick specimen and indicates that no improvement is obtained by decreasing the thickness to 0.1 in., as predicted in Table 6. Phelps and Loginow (19) have shown that 0.020- to 0.050-in.-thick sheets of PH 15-7Mo and 17-7 PH in the RH 950 and TH 1050 conditions are susceptible to stress-corrosion cracking. Again, this is consistent with data in Table 6.

CONCLUSIONS

1. The fracture toughness K_{Ic} and stress-corrosion threshold K_{Iscc} have been determined for a variety of high-strength, precipitation-hardening stainless steels. The material evaluated included 17-7 PH, PH 15-7Mo, AM 355, AM 362, AM 364, 17-4 PH, 15-5 PH, PH 13-8Mo, and Custom 455.

2. The stress-corrosion resistance and fracture toughness of the semi-austenitic steels (17-7 PH, PH 15-7Mo, and AM 355) is generally lower that that of the martensitic steels.

3. There is a general trend for K_{Iscc} to increase with K_{Ic}; a number of martensitic steels appear to be immune to stress-corrosion cracking in 3.5% aqueous sodium chloride solution.

4. Fracture mechanics analysis indicates that unless very high standards of nondestructive testing are employed, there is a definite possibility of failure at applied stresses approaching the yield point in all materials found to be susceptible to stress-corrosion cracking.

5. Comparison of precracked-specimen and smooth-specimen data for certain materials reveals discrepancies. These are explained in terms of the necessity for pit development in the smooth specimens.

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Table 1.   Chemical composition of the stainless steels studied (weight percent)

Steel	Heat	Form	Cr	Ni	Al	Ti	Mo	Cu	Cb	C	Mn	Si	S	P
17-7 PH	36882	1-3/4-in.-sq bar	17.00	7.30	1.22	0.088	0.16	0.20	0.01	0.069	0.57	0.31	0.010	0.023
PH 15-7Mo	57042	1-3/4-in.-sq bar	15.32	7.06	1.07	0.080	2.24	0.21	0.02	0.071	0.59	0.37	0.010	0.019
Am 355	---	2-1/2-in.-sq bar	15.0	4.15			2.6			0.113	0.8	0.3	0.011	0.012
AM 362	BA65640	2-1/4-in./dia bar	14.65	6.52	0.055	0.89	0.080	0.17		0.047	0.21	0.19	0.010	0.016
AM 364	26316	3- x 12- x 24-in. billet	11.10	11.20	0.61	0.22				0.011	0.05 max	0.05 max	0.003	0.010 max
17-4 PH	67272	1-3/4-in.-sq bar	16.07	4.25				3.36	0.25	0.038	0.22	0.62	0.013	0.015
15-5 PH (air melted)	36051	3-in.-sq billet	15.29	4.77			0.09	3.35	0.20	0.043	0.27	0.39	0.013	0.017
15-5 PH (vacuum melted)	1V0127	4-1/2-in.-sq billet	14.98	4.69			0.03	3.23	0.26	0.035	0.21	0.40	0.005	0.015
PH 13-8Mo	2V0037	4-in.-sq billet	13.03	8.30	1.06		2.14			0.032	0.01	0.03	0.005	0.002
Custom 455	84383	4-in.-sq billet	11.83	8.53		1.27		2.21	0.26	0.014	0.03	0.15	0.005	0.008

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Table 2.   Heat treatment of the stainless steels studied

Material	Condition	Heat treatment
17-7 PH* and PH 15-7Mo*	RH 950	1750°F, 1 hr, air cooled to room temperature. Cooled to -100°F within 40 hr and held 8 hr. Aged at 950°F, 1 hr, air cooled.
	TH 1050	1400°F, 1-1/2 hr, cooled to 60°F within 1 hr of removal from furnace and held 30 min. Aged at 1050°F, 1-1/2 hr, air cooled.
AM 355*	SCT 850	1750°F, 1 hr, water quenched. Cooled to -100°F, held 3 hr. Aged at 850°F, 3 hr, air cooled.
	SCT 1000	1750°F, 1 hr, water quenched. Cooled to -100°F, held 3 hr. Aged at 1000°F, 3 hr, air cooled.
	Modified SCT 1000**	1900°F, 3/4 hr, water quenched. Cooled to -100°F, held 3 hr. 1710°F, 1 hr, air cooled. Cooled to -100°F, held 3 hr. Aged at 1000°F, 3 hr, air cooled.
AM 362	H 900	1575°F, 1 hr, air cooled. Aged 900°F, 8 hr, air cooled.
	H 1000	1575°F, 1 hr, air cooled. Aged 1000°F, 1 hr, air cooled.
AM 364	H 850	1500°F, 1 hr, air cooled. Cooled to -100°F, held 5 hr. Aged 850°F, 4 hr, air cooled.
	H 950	1500°F, 1 hr, air cooled. Aged 950°F, 4 hr, air cooled.
17-4 PH and 15-5 PH (air melted and vacuum melted)	H 900	Aged 900°F, 1 hr, air cooled.
	H 1000	Aged 1000°F, 1 hr, air cooled.
PH 13-8Mo	H 950	Aged 950°F, 4 hr, air cooled.
Custom 455	H 950	1500°F, 1 hr, water quenched. Aged 950°F, 4 hr, air cooled.

*Semiaustenitic steels; others are martensitic.

**This treatment was added because it was reported (6) to improve the stress-corrosion resistance.

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Table 3.   Tensile properties of the stainless steels studied

Material	Heat treatment	Tensile yield strength (ksi)	Tensile ultimate strength (ksi)	Elongation (%)
17-7 PH	RH 950	171.3	186.5	11
	TH 1050	--	197.2	9
PH 15-7Mo	RH 950	196.5	219.4	12
	TH 1050	167.8	178.2	11
AM 355	SCT 850	180.0	213.5	17
	SCT 1000	171.2	178.0	19
	Modified SCT 1000	163.2	173.4	18
AM 362	H 900	197.0	200.5	11
	H 1000	175.0	178.9	14
AM 364	H 850	183.3	188.7	15
	H 950	186.7	191.5	15
17-4 PH	H 900	176.5	194.6	14
	H 1000	157.9	162.2	15
15-5 PH (air melted)	H 900	175.0	195.7	16
	H 1000	157.9	161.6	16
15-5 PH (vacuum melted)	H 900	174.9	191.5	14
	H 1000	157.6	162.9	15
PH 13-8Mo	H 950	207.5	225.1	14
Custom 455	H 950	246.0	247.0	11

Table 4. Fracture toughness and stress-corrosion threshold values of the stainless steels studied

Material	Heat treatment	K_{Ic} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$)
17-7 PH	RH 950	32.3	< 19.0
	TH 1050	38.7	15.8 ± 1.0
PH 15-7Mo	RH 950	31.5	14.0 ± 2.0
	TH 1050	33.6	18.5 ± 2.0
AM 355	SCT 850	59.2	32.5 ± 3.0
	SCT 1000	88.4*	88.4**
	Modified SCT 1000	117*	117
AM 362	H 900	30.2	12.5 ± 2.0
	H 1000	40.1	31.0 ± 3.0
AM 364	H 850	131*	93 ± 7
	H 950	128*	128**
17-4 PH	H 900	51.5	51.5**
	H 1000	119*	119**
15-5 PH (air melted)	H 900	96.8*	80.0 ± 2.0
	H 1000	114*	114**
15-5 PH (vacuum melted)	H 900	74.5	55.8 ± 3.8
	H 1000	120*	120**
PH 13-8Mo	H 950	73.9	73.9**
Custom 455	H 950	72.1	72.1**

*Test did not meet ASTM requirements for valid K_{Ic} determination.

**No stress-corrosion crack growth at stress-intensity levels exceeding approximately 85% K_{Ic}.

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Table 5. Effect of overaging on fracture toughness and stress-corrosion properties of stainless steels studied

Material	Improvement due to overaging (%)	
	K_{Ic}	K_{Iscc}
AM 355	43	160
AM 362	33	148
AM 364	0	48
17-4 PH	132	132
15-5 PH (air melted)	18	43
15-5 PH (vacuum melted)	61	115

Table 6.   Minimum thickness required for plane-strain conditions
            in the stainless steels studied

Material	Heat treatment	Thickness (in.)
17-7 PH	RH 950	<0.031
	TH 1050	0.020
PH 15-7Mo	RH 950	0.012
	TH 1050	0.030
AM 355	SCT 850	0.081
AM 362	H 900	0.010
	H 1000	0.078
AM 364	H 850	0.65
15-5 PH (air melted)	H 900	0.52
15-5 PH (vacuum melted)	H 900	0.2
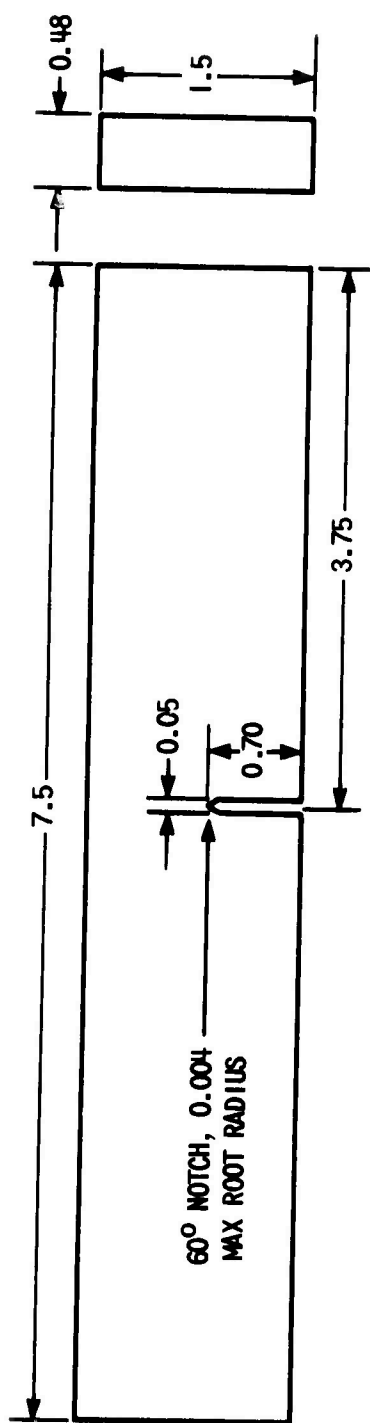
DIMENSIONS IN INCHES

(a) for fracture toughness tests.

0.48

1.5

7.5

3.75

0.05

0.70

60° NOTCH, 0.004 MAX ROOT RADIUS

(b) for stress-corrosion tests.

0.48

1.5

7.5

3.75

0.225
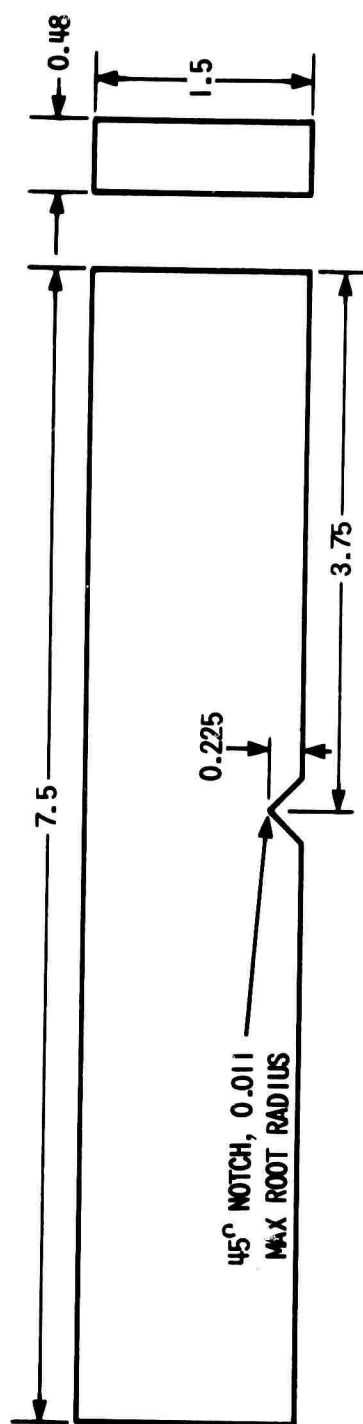
45° NOTCH, 0.011 MAX ROOT RADIUS

Figure 1   Geometry of single-edge-notched specimens.
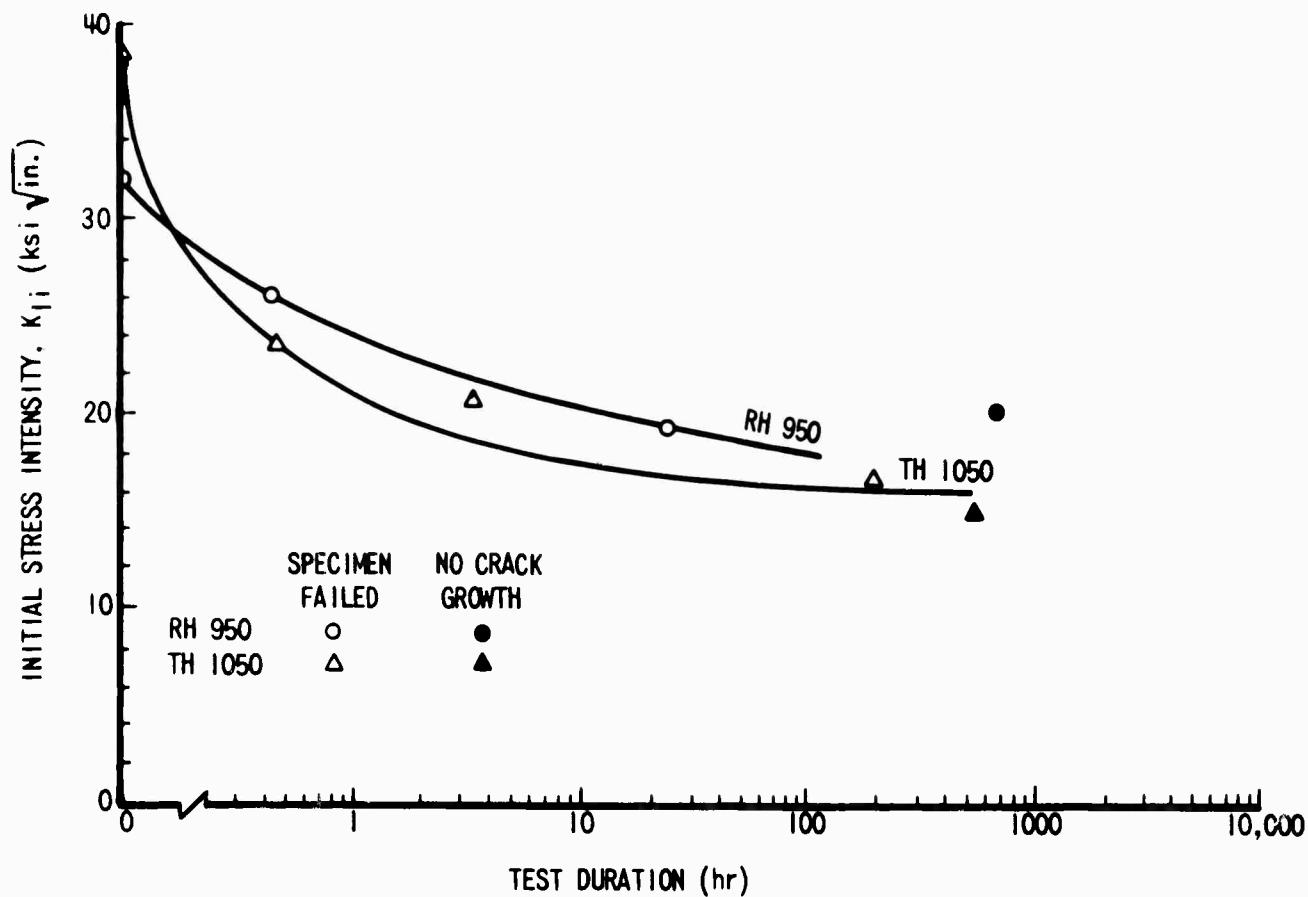
Figure 2   Stress-corrosion test results for 17-7 PH.
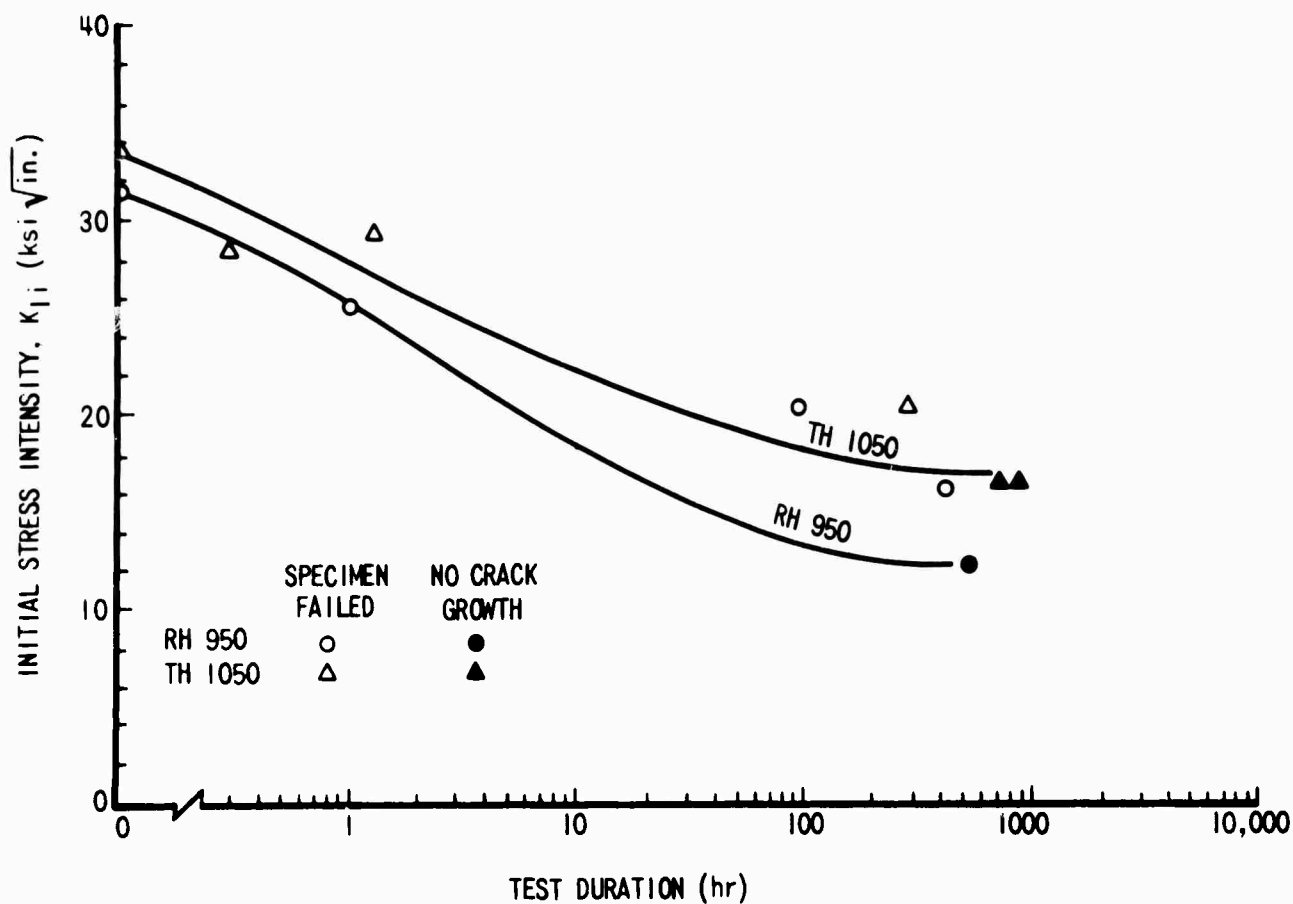
Figure 3   Stress-corrosion test results for PH 15-7Mo.
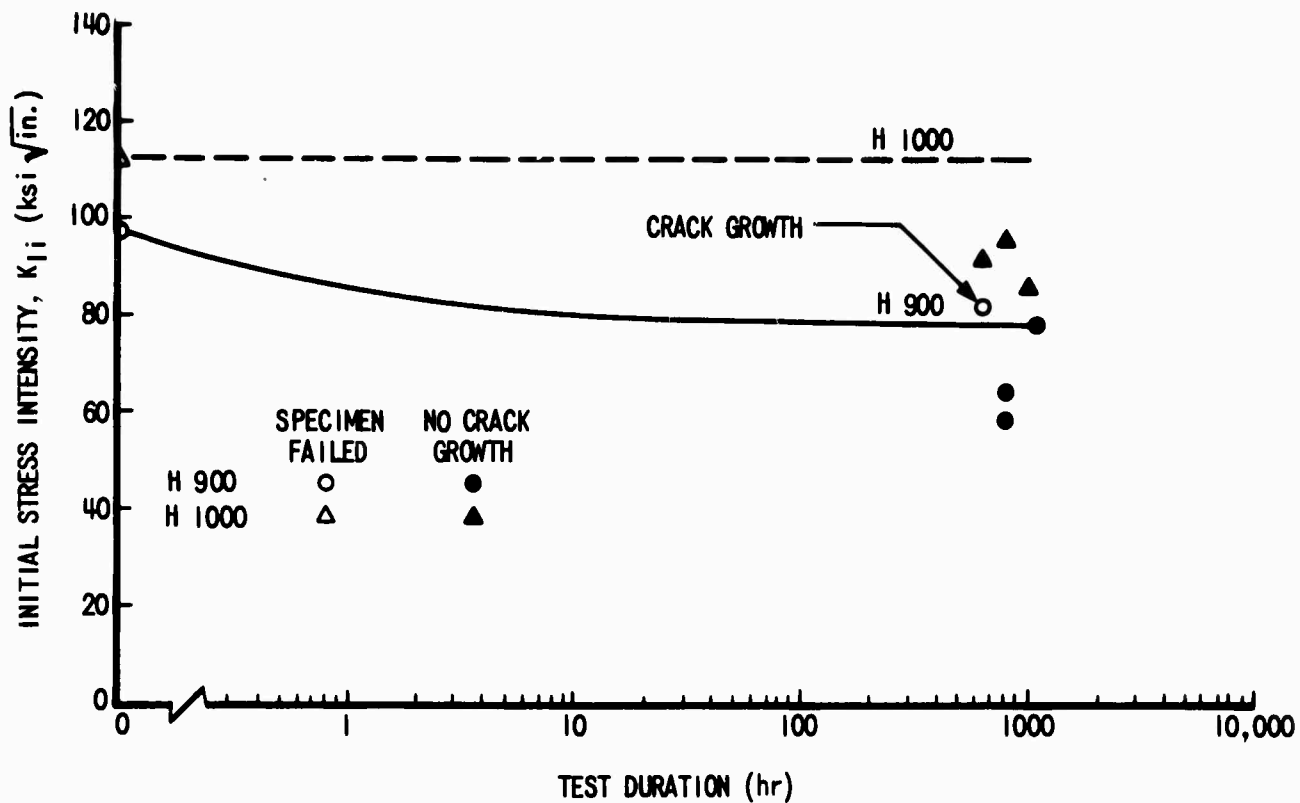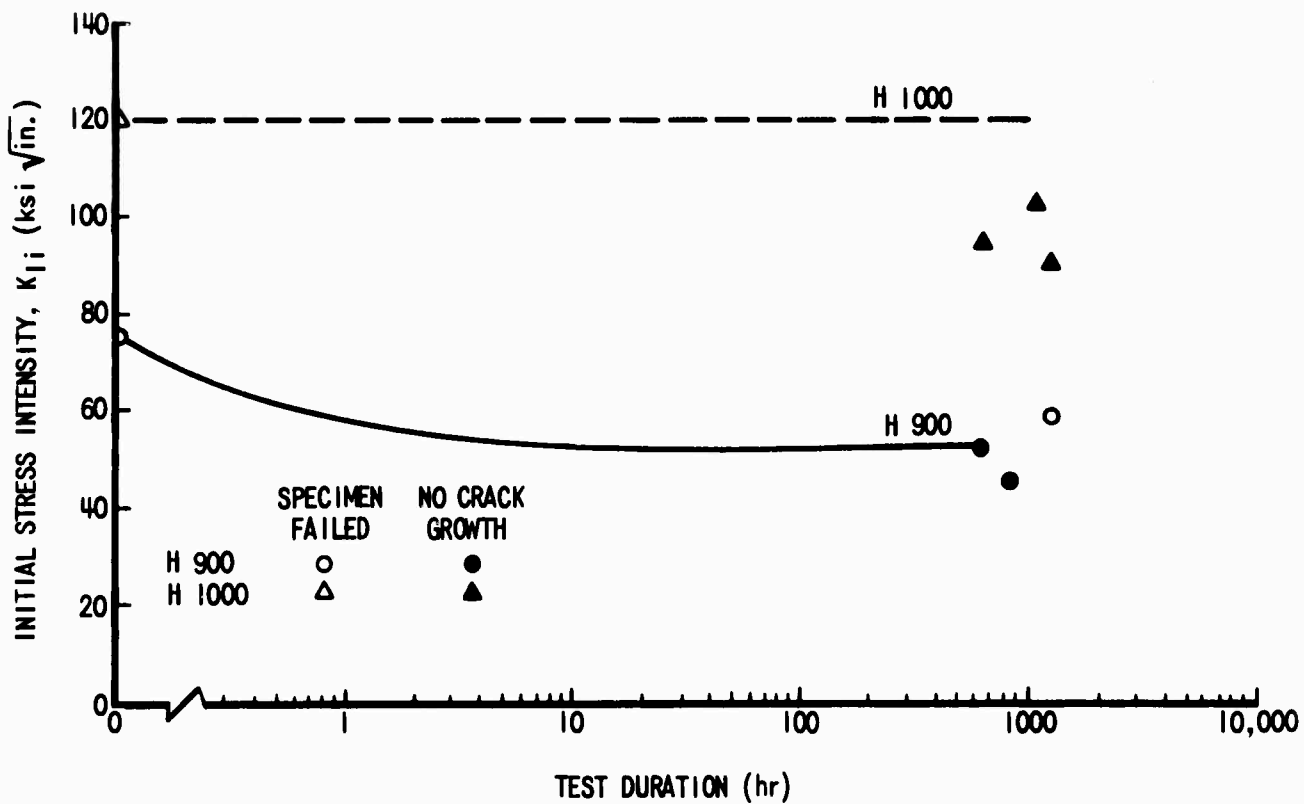
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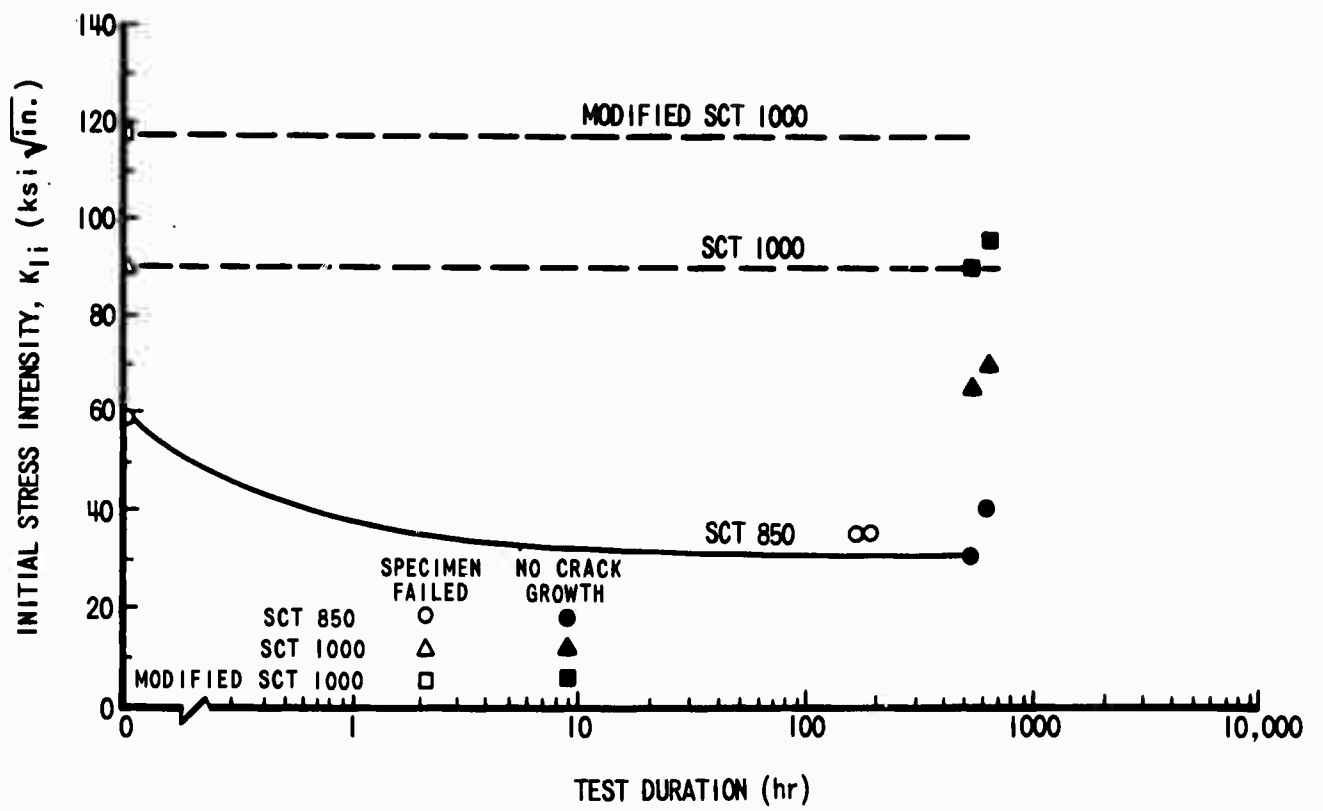
Figure 4   Stress-corrosion test results for AM 355.
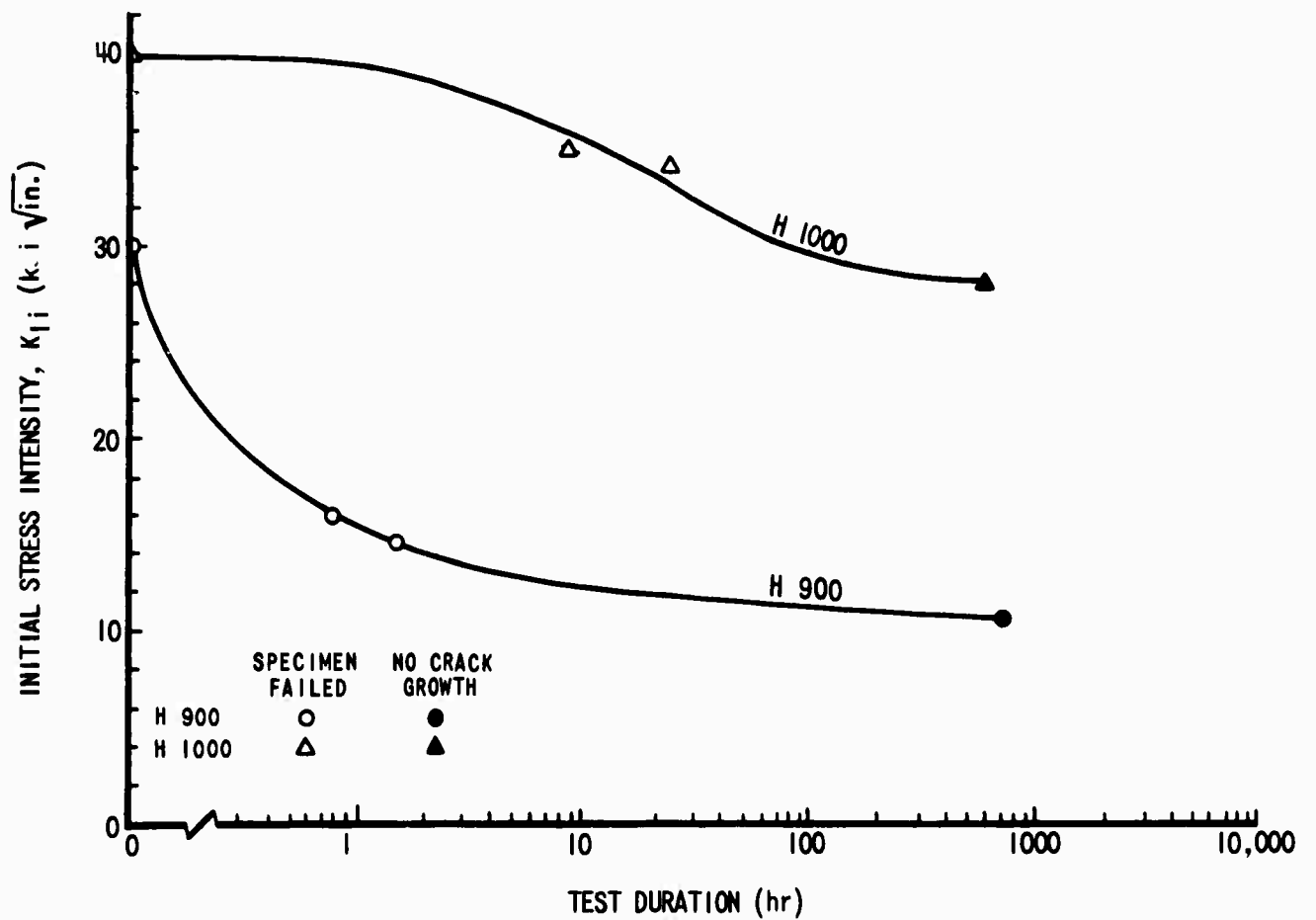
Figure 5   Stress-corrosion test results for AM 362.

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Figure 6   Stress-corrosion test results for AM 364.

Figure 7   Stress-corrosion test results for 17-4 PH.

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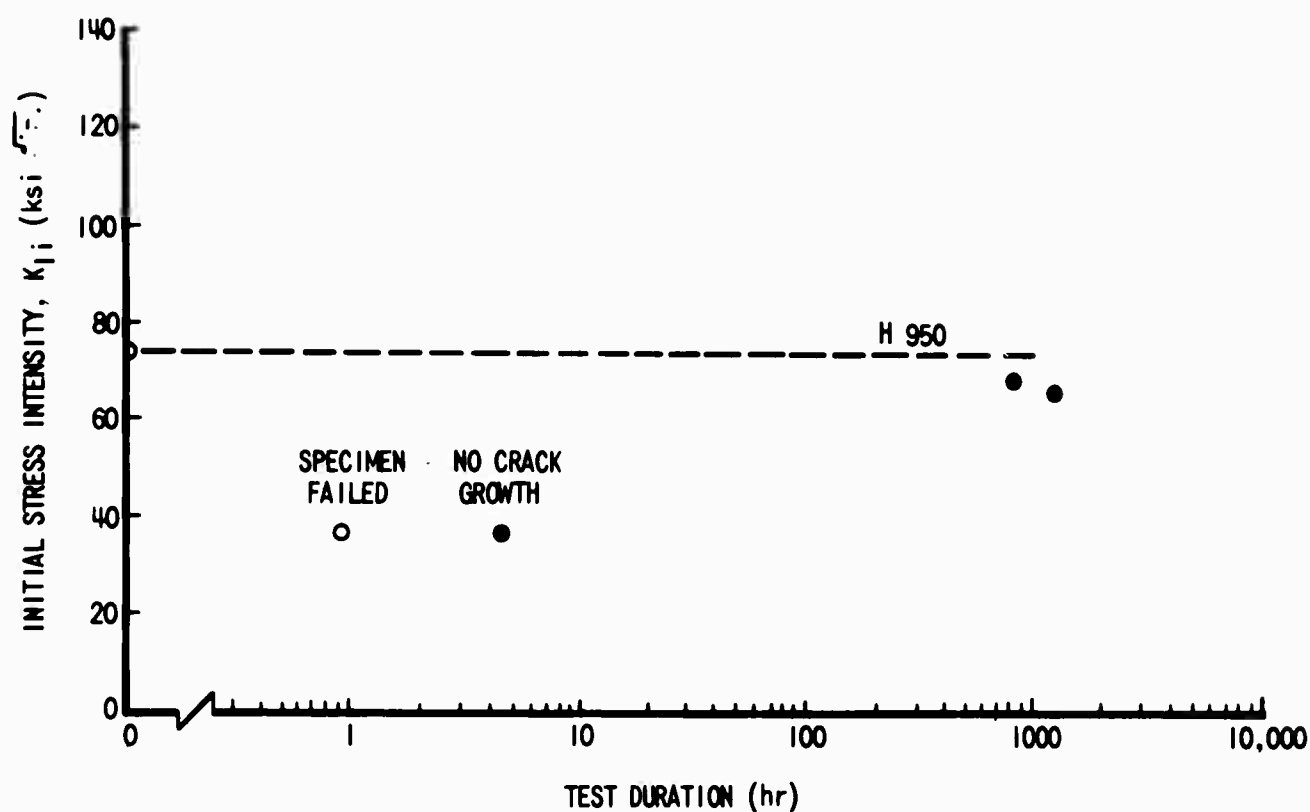Figure 8   Stress-corrosion test results for 15-5 PH (air melted).

Figure 9   Stress-corrosion test results for 15-5 PH (vacuum melted).

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Figure 10   Stress-corrosion test results for PH 13-8Mo.
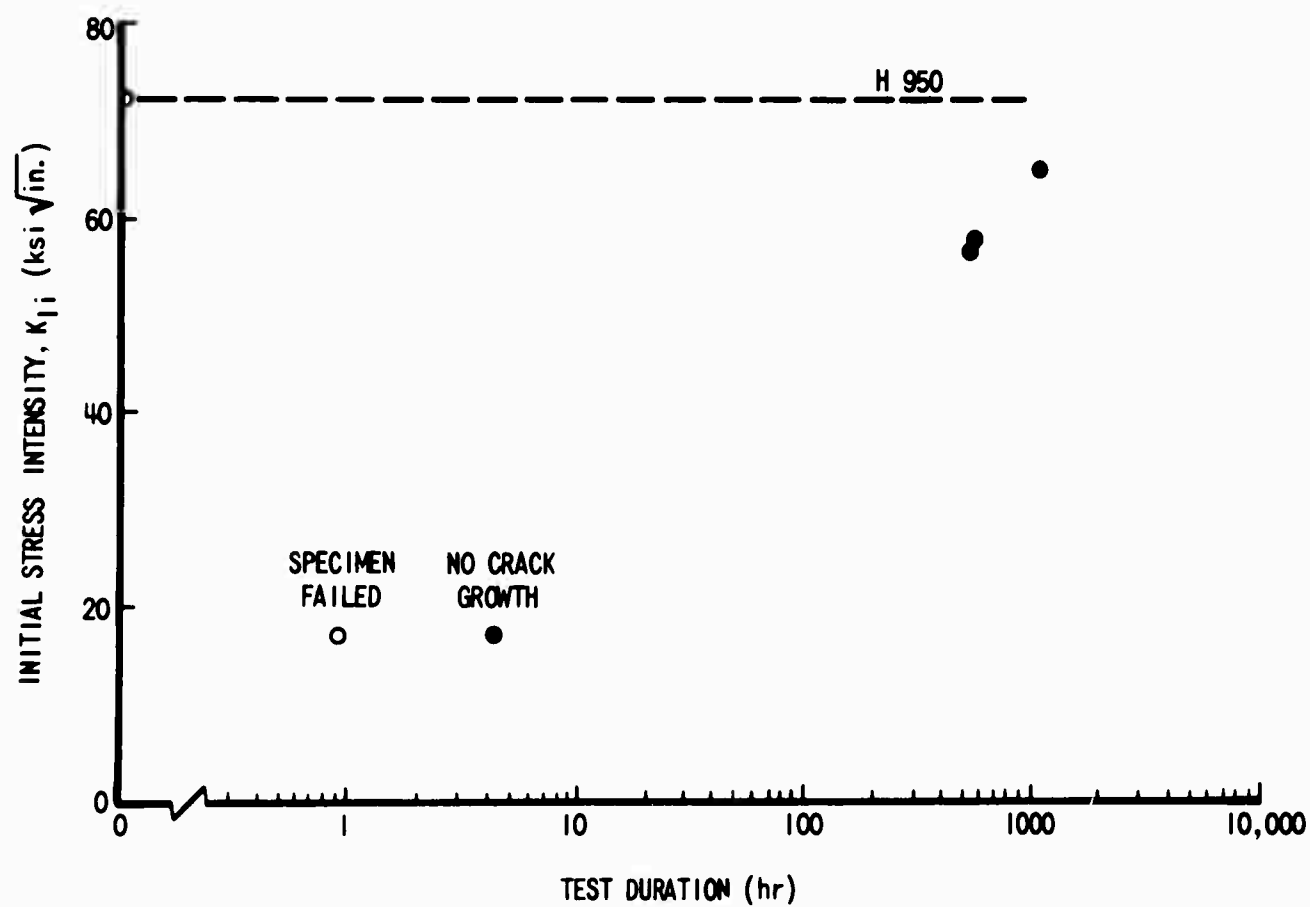
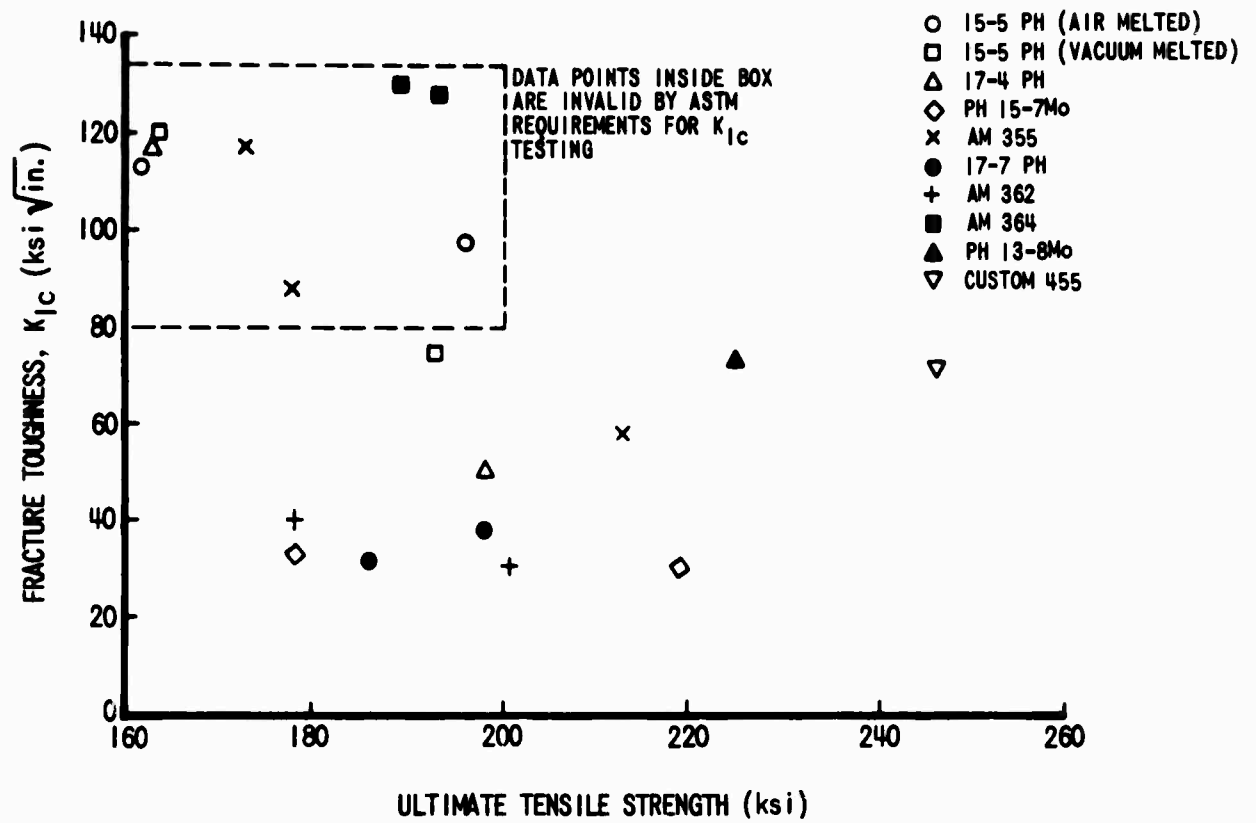Figure 11   Stress-corrosion test results for Custom 455.

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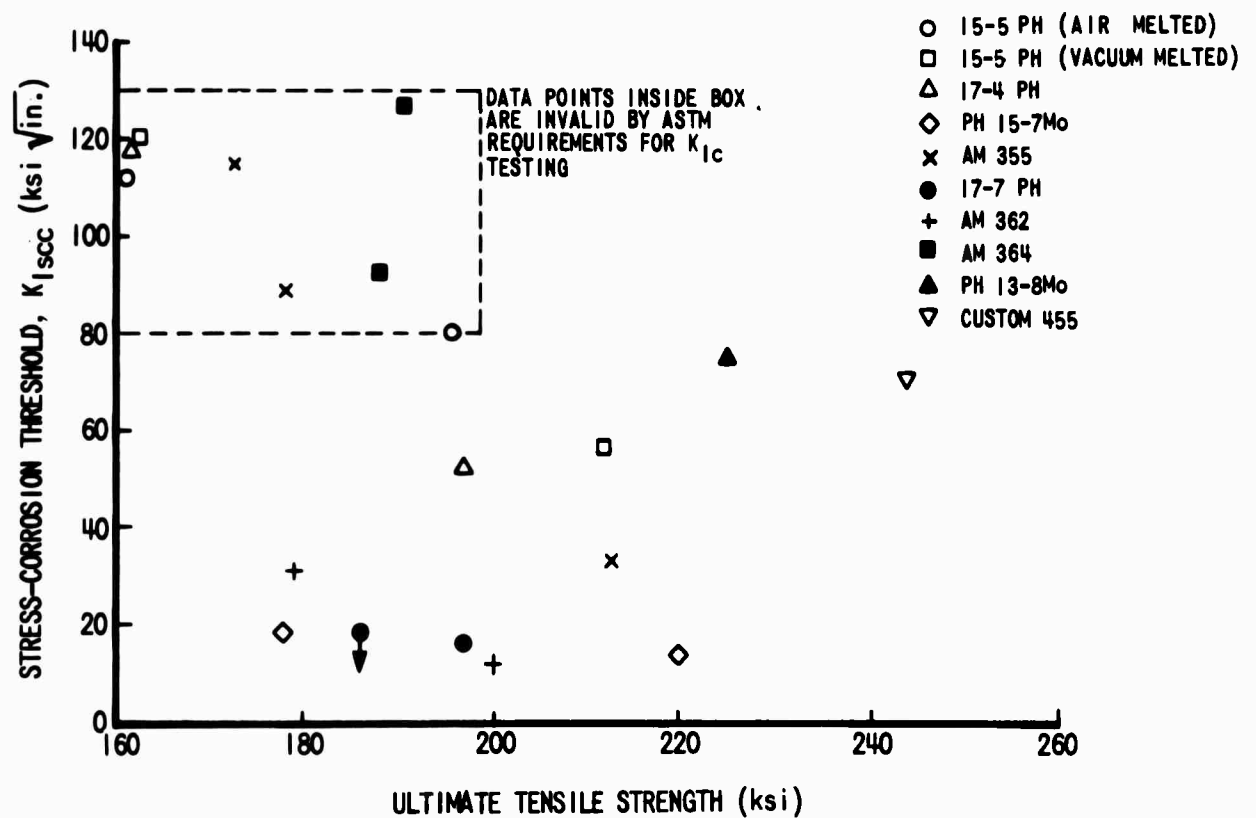Figure 12   Relation between fracture toughness and strength.

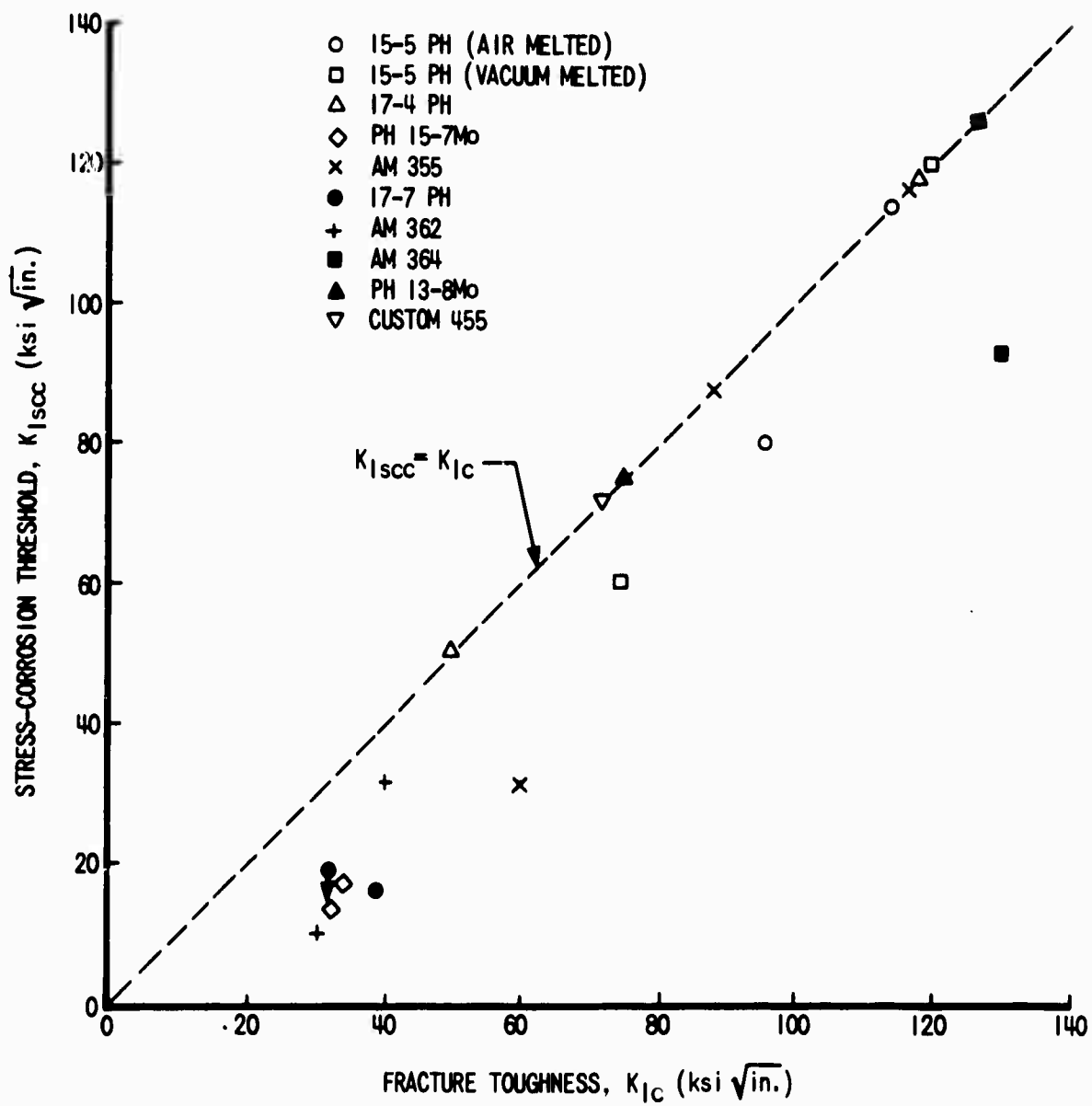Figure 13   Relation between stress-corrosion properties and strength.

Figure 14   Relation between K_{Iscc} and K_{Ic}.

Figure 15   Intergranular stress-corrosion cracking in semiaustenitic
             stainless steel 17-7 PH (TH 1050) (X4,000).

Figure 16   Intergranular stress-corrosion cracking in martensitic
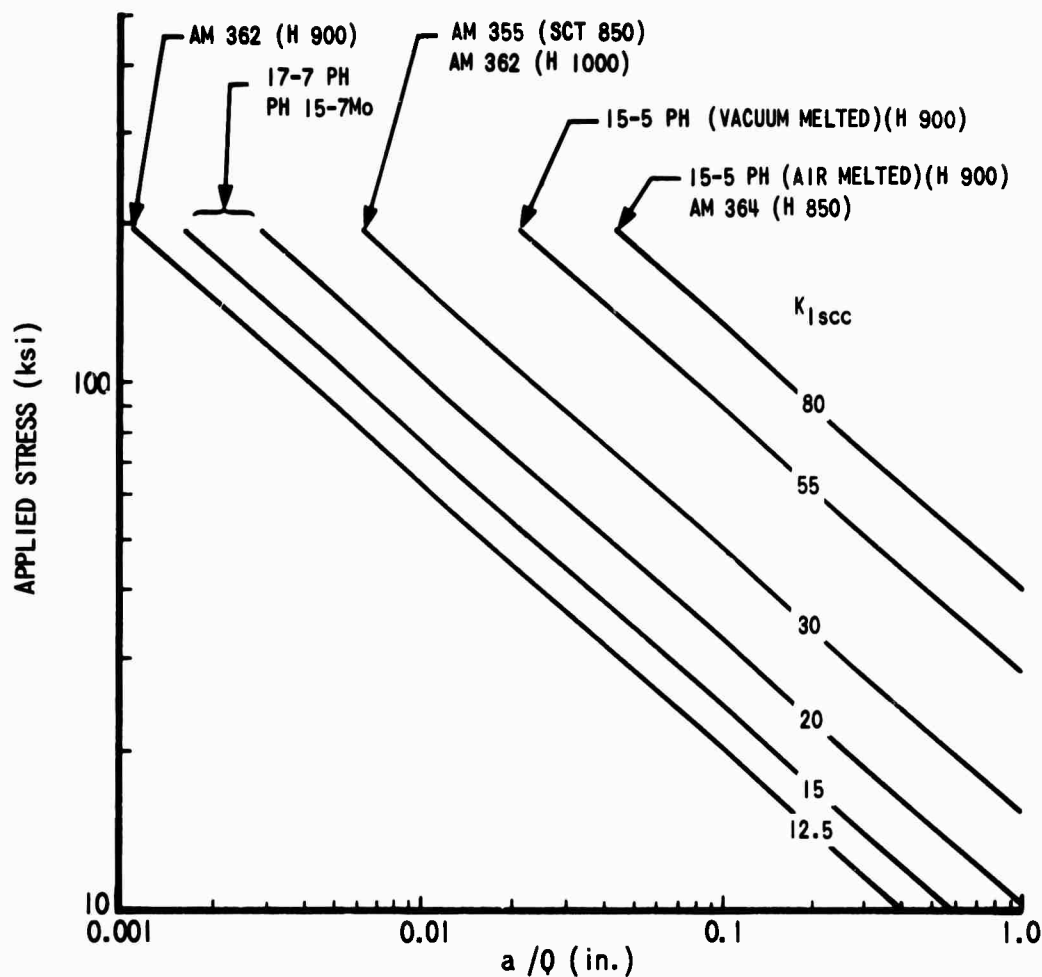   stainless steel AM 362 (H 900) (X4,000).

Figure 17   Relation between applied stress and crack length for
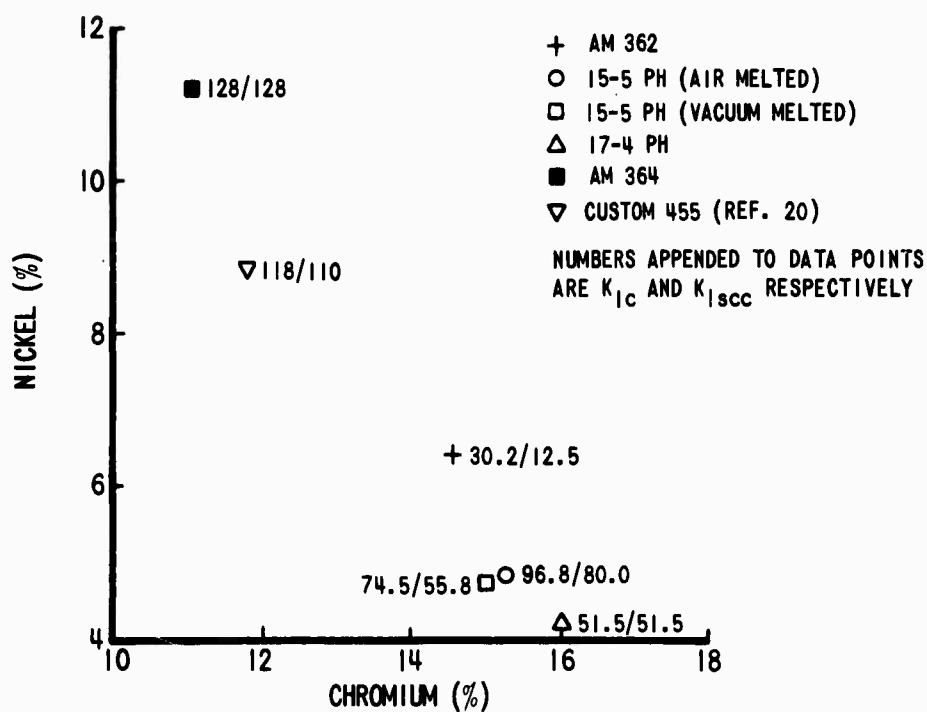   initiation of stress-corrosion cracking.

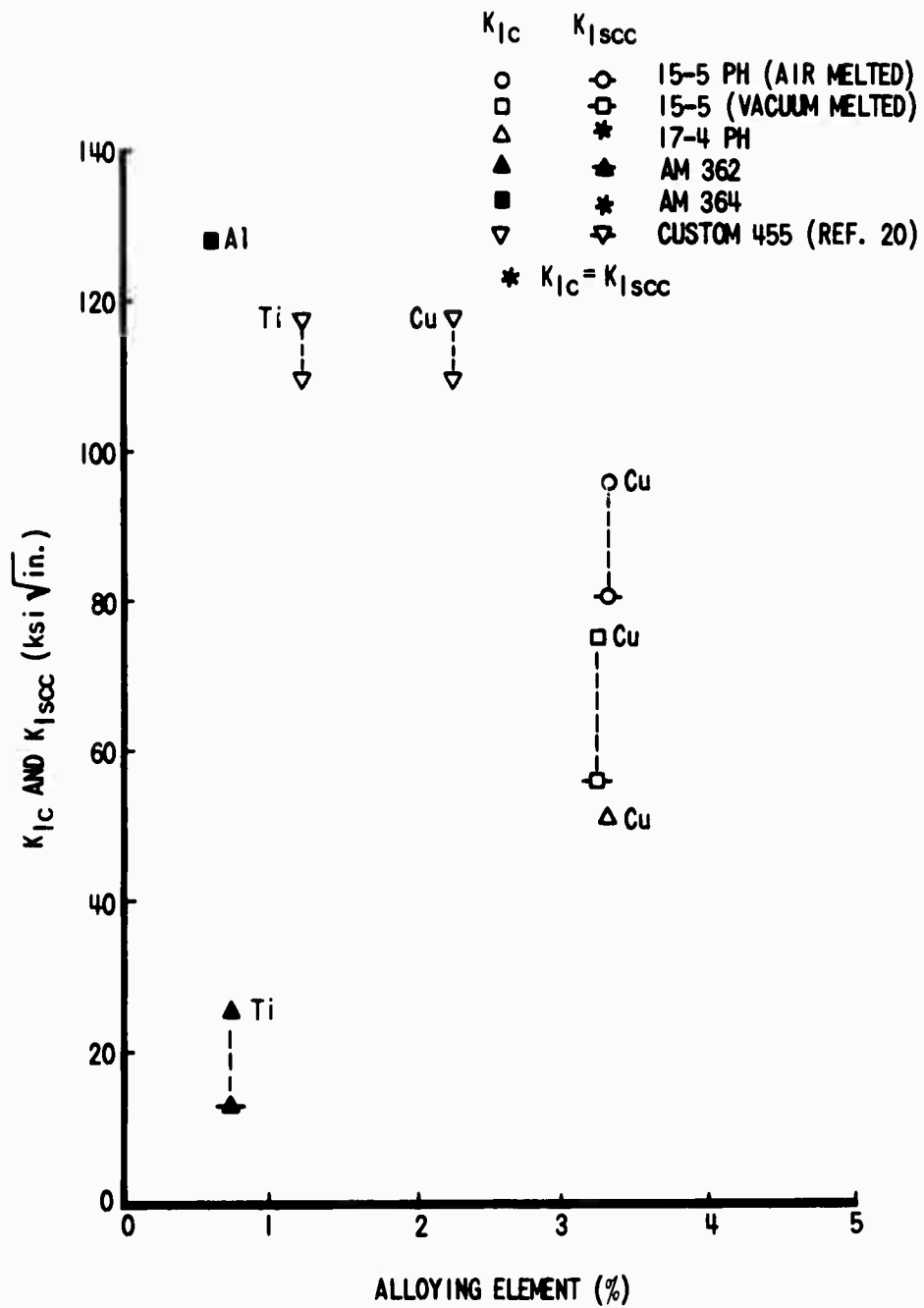Figure 18   Effect of nickel and chromium on K_{Ic} and K_{Iscc}.

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K_{Ic} K_{Iscc}

○   ⬡   15-5 PH (AIR MELTED)
□   ⬓   15-5 (VACUUM MELTED)
△   ✳   17-4 PH
▲   ⬟   AM 362
■   ✳   AM 364
▽   ⬇   CUSTOM 455 (REF. 20)

✳ K_{Ic}= K_{Iscc}

■ Al

Ti ▽

Cu ▽

○ Cu

○

□ Cu

⬓

△ Cu

▲ Ti

▲

K$_{Ic}$ AND K$_{Iscc}$ (ksi $\sqrt{\text{in.}}$)

ALLOYING ELEMENT (%)

Figure 19   Effect of alloying elements on K_{Ic} and K_{Iscc}.

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13. ABSTRACT

The plane-strain fracture toughness K_{Ic} and stress-corrosion threshold K_{Iscc} have been determined for the following high-strength, precipitation-hardening steels: 17-7 PH (RH 950, TH 1050), PH 15-7Mo (RH 950, TH 1050), AM 355 (SCT 850, SCT 1000), AM 362 (H 900, H 1000), AM 364 (H 850, H 950), 17-4 PH (H 900, H 1000), 15-5 PH air melted and vacuum melted (H 900, H 1000), PH 13-8Mo (H 950), and Custom 455 (H 950). Correlations of K_{Iscc} with service performance, smooth-specimen test data, and chemical composition are discussed.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Stress Corrosion						
Fracture Mechanics						

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